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Conceptual design of a divertor Thomson scattering diagnostic for NSTX-U[a]

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A conceptual design for a divertor Thomson scattering (DTS) diagnostic has been developed for the NSTX-U device to operate in parallel with the existing multipoint Thomson scattering (MPTS) system. Higher projected peak heat flux in NSTX-U will necessitate application of advanced magnetics geometries and divertor detachment. Interpretation and modeling of these divertor scenarios will depend heavily on local measurement of electron temperature, T_e, and density, n_e, which DTS provides in a passive manner. The DTS design for NSTX-U adopts major elements from the successful DIII-D DTS system including 7-channel polychromators measuring T_e to 0.5 eV. If implemented on NSTX-U, the divertor TS system would provide an invaluable diagnostic for the boundary program to characterize the edge plasma.

I. INTRODUCTION

A Thomson scattering (TS) diagnostic system [1,2] applied in a Tokamak divertor offers a powerful means of measuring local plasma conditions in the targets and divertor legs directly and compliment TS measurements made upstream in the core/pedestal/edge region. The measurement is passive in that negligible impact (<1%) is made to local plasma conditions by the laser [3], and without the need for interpretation of saturation current/voltage characteristics and other limitations affecting Langmuir probes. However, the proximity of the measurement volume of scattered light to the plasma-facing surface in the device leads to significant stray light which can easily overwhelm the measurement and its calibration. For this reason, the number of devices with divertor Thomson scattering (DTS) diagnostic systems has been very limited: previously ASDEX-U [4], and currently DIII-D [5,6,7]. For the future, however, DTS systems are currently planned for MAST [8] and ITER [9], each with similar plans for baffling of the laser path, temporal isolation of the scattered light detection, and other techniques for stray-light rejection and calibration as demonstrated by ASDEX-U/DIII-D.

For NSTX-U, increased heating power (≤19 MW up from ≤8 MW), plasma current (2 MA up from 1 MA) and toroidal magnetic field (1 T up from 0.5 T) in comparison to the previous NSTX [10] is estimated to increase peak divertor inter-ELM heat flux in NSTX-U to ~24 MW/m^2 or more compared to a peak of ~10 MW/m^2 previously [11]. This level of power handling will necessitate regular use of heat flux mitigation, including operation with a detached divertor, and use of high flux expansion and snowflake magnetic equilibriums [12]. Interpretation and modeling of these divertor scenarios will depend heavily on measurement of electron temperature, density, and pressure – the key physical parameters that control the detachment process.

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II. INTERNAL CONFIGURATION

Key to the design of the DTS system on NSTX-U will be to compliment and expand upon the existing Multi-point Thomson Scattering (MPTS) system [13] which has undergone modification and upgrade for the transition to NSTX-U [14,15]. By their nature, the low aspect ratio spherical torus design on which NSTX-U is based ($A=R/a\geq1.5$), provides very little access by vertically-viewing ports at small major radius. Here, dense magnetic coil interconnects leave no room for diagnostic access, for example, a port for DTS laser entry and high power dump at the exit, and a port at a perpendicular location for viewing optics of scattered light. Instead of a traditional vertical laser chord, an inclined tangential laser path is chosen for the NSTX-U DTS system as shown in Figure 1, similar to the nearly radial laser path used by the MPTS, with a downward viewing port viewing TS light with scattering angles of ~70-110°.

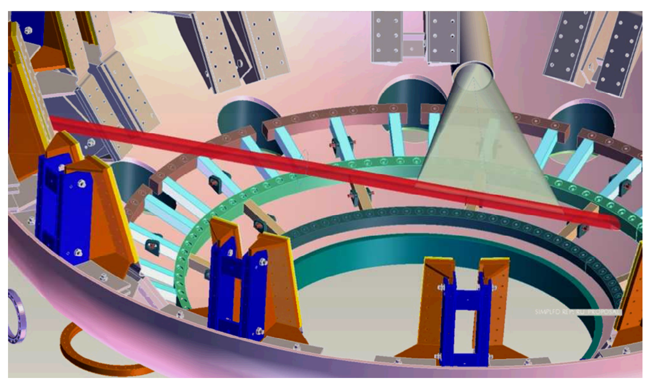

Figure 1: CAD model of proposed DTS tangential laser path through the NSTX-U vessel (cylinder from upper left to middle right), and diagonal, near-perpendicular optical viewing path (upper right).

A poloidal projection of the diagonal viewing plane that results from this viewing geometry is shown in Figure 2. In this configuration, the outer divertor leg and target may be fully characterized with the application of strike-point/X-point sweeping along the lower outer baffle plate and remapping of data in $\Psi_n/L_{poloidal}$ space to a single equilibrium. This technique has been successfully applied at DIII-D which also benefits from an open divertor where sweeping leads to little impact to divertor conditions [7,16]. This viewing configuration would also maximize the effectiveness of the DTS system to characterize plasma-surface interaction near the planned Material Analysis Particle Probe (MAPP) [17], and provide T_e, n_e values essential for determining fuel and impurity particle densities from measured photon emission via SXB/DXB values in the ADAS [18] or other atomic/molecular emission databases.

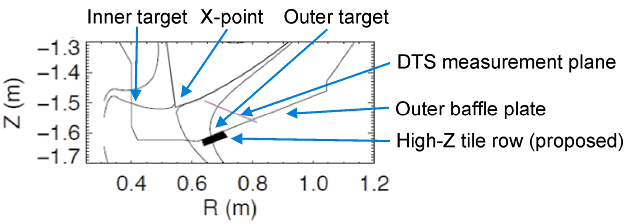

Figure 2: Poloidal projection of the DTS measurement plane along the outer divertor in NSTX-U.

2D characterization of the divertor plasma is also an invaluable constraint for state-of-the-art boundary modeling codes such as SOLPS, EDGE-2D, UEDGE, OEDGE, and WBC/REDEP.

III. EXTERNAL CONFIGURATION

The laser proposed for the DTS system is similar to that used by most established core/edge TS systems (including the NSTX MPTS), a Q-switched, short pulse (5-12 ns), high repetition rate (10-50Hz) Nd:YAG class IV with 0.5-2.0 J and low divergence (≤0.5 mrad). Beam expansion would be incorporated to reduce divergence along the length of the beam path. Available resources would determine repetition rate and pulsed energy whose cost varies considerably with performance.

Use of a co-linear Helium Neon (HeNe) laser allows efficient alignment between plasma discharges as aiming optics are affected by changes in ambient temperature and other vibrations. Turning mirrors incorporate high power Y-H (YAG and HeNe) coatings in order to maximize laser energy delivery to the vessel and incorporate digital cameras (shielded where necessary in the test cell) on the backside to view the small (<1% of YAG, <20% of HeNe) transmitted portion of laser and HeNe light. 3 turning mirror mounts would be fitted with nano-positioning piezoelectric capability for alignment purposes. The first turning mirror would incorporate a fast piezo-electric steering system similar to that utilized by the C-Mod laser blowoff system [19] in order to co-lineate multiple lasers in the DTS path to increase the effective pulse rate for the system, and prevent the need for larger optics along the laser path to accommodate a pack of adjacent laser paths.

Critically important for study of low temperature plasmas associated with divertor detachment will be the capability to measure T_e of <1 eV to evaluate the dominant physics processes occurring in the divertor region. Attached (T_e~20-40 eV) and high recycling (T_e ~7-10 eV) divertor conditions are dominated by kinetic effects, parallel conduction and fuel/impurity radiation. In contrast, the relatively cold and dense divertor plasma regime in partial (T_e ~2-3 eV) and full detachment (T_e~0.5-1.0 eV) are complicated by charge-exchange power losses, volume recombination, and the presence of molecular/neutral fluid near the strike point region. While relatively poorly diagnosed and modeled to date, these processes are thought to be of great importance for understanding of detachment phenomena, accurately simulating the divertor, and projecting performance of future devices like FNSF, ITER, and DEMO.

The NSTX-U DTS system will accomplish this using specially optimized polychromators [20] incorporating state-of-the-art ultrahigh transmission, thin bandpass filters. Now available commercially from Alluxa Incorporated [21], these filters are magnetron 'hard' coated for long guaranteed lifetime performance (20+ years compared to ~5 years for traditional 'soft' coated filters), and provide simultaneous specifications of a) down to <1 nm full width at half maximum (FWHM), b) 97+% peak flat-top transmission, and c) at least 10^5 (OD5) out-of-band blocking for stray light rejection. Filters are mounted in each polychromator corresponding to a single viewing channel along the DTS measurement plane with a 4° angle with respect to the incoming light and 4° cone angle. While the non-perpendicular AOA leads to broadening of the transmission profile, the ultrathin bandpass makes even the broadened profile sufficiently thin for ultra-low T_e measurement.

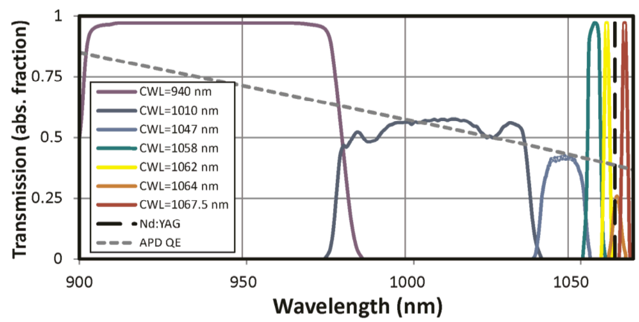

Figure 3: 7-channel polychromator filter design for the NSTX-U DS system compared to the APD sensitivity vs. wavelength.

Polychromators will incorporate high speed Avalanche photodiode detectors (APD) with onboard thermoelectric temperature control [22] and water-cooling to maintain ±0.1°C thermal stability, and low-noise A/D plus sample-and-hold electronic circuitry for efficient background subtraction [23] and to facilitate cost savings compared to a distributed fully digitized acquisition system as used at MAST [24]. Data acquisition is proposed to be based on 16-bit, 500 k-sample/s D-TACQ system [25] to maximize the signal-to-noise ratio (SNR).

Low-OH, pure fused silica fiber bundles are used for each chord viewing the laser with ~1 cm spatial resolution. Viewing optics will incorporate radiation-tolerant cerium-doped optical materials [26] to prevent browning due to accumulation of neutron and gamma exposure which would lead to transmission loss preferentially at shorter wavelengths. High transmission (92+%) and contrast (120-300) nanowire-grid polarizers [27] will be used in the optical path to half background stray light prominent when attempting to measure TS light near a surface.

IV. PROJECTED PERFORMANCE

Low temperature performance is maximized by staggering the spectral separation of the Nd:YAG laser line (1064.3 nm) and the CWL for each of the closest three bandpass (BP) filters to the laser ($\Delta\lambda_{YAG\text{-}BPx}$, x=1-3). In the picture shown below, filters are chosen such that the nearest to the laser line, with center wavelength (CWL) at 1062 nm, is just to the blue of 1064.3 nm, then the next at 1067.5 nm to the red, then the next further to the blue (1058 nm).

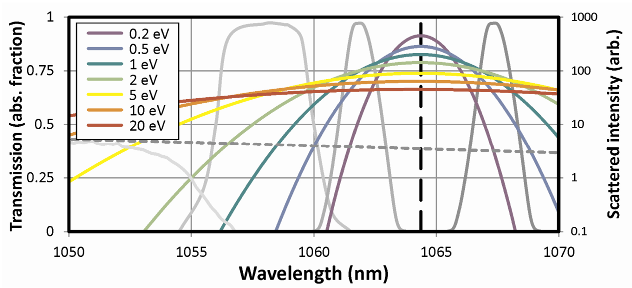

Figure 4: Close-up showing polychromator filter transmission profiles near the Nd:YAG laser line, overlaid with Thomson scattered spectra for T_e=02.5 to 20 eV.

Incorporation of the 7-element polychromator filter set as described will result in the fractional error in T_e measurement as shown in Figure 5. The T_e regime where $\delta T_e/T_e \leq 10\%$ is projected to extend from 0.2 eV up to >5 keV, a dynamic range of >4 orders of magnitude. This model does not incorporate specific details of laser mode (i.e., energy outside of the ideal TEM00), energy losses along the beam path and due to misalignment, noise in scattered light detection, etc., but is expected to be within a factor of 2 of accurate. Measurable n_e is expected in the range of $5\times10^{18} - 1\times10^{21}$ /m^3.

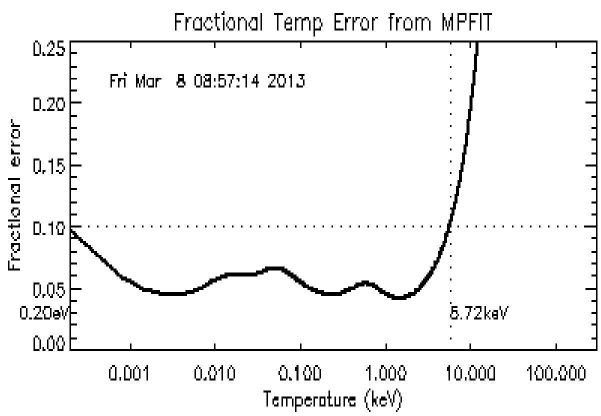

Figure 5: Projected fractional error in the T_e measurement by the proposed DTS system for NSTX-U.

Calibration will include spectral calibration of polychromator filters, and measurement of absolute optoelectronic intensity sensitivity of the APD detectors for putput gains, statistical dark noise, and pulsed channel noise as a function of background light. Due to the thin bandpass of filters proposed to achieve T_e<1 eV performance, the former process will require accurate measurement of the instrumental width (i.e., the 1-D point-spread function) of the spectrometer used and deconvolution of the measured transmission profile with this function using a maximum entropy or maximum likelihood algorithm. This will ensure accurate determination of the true transmission peak and bandpass profile of the filters in the system and improve the T_e measurement accuracy.

Additionally, both standard Rayleigh and rotational Raman calibration procedures may be carried out for the DTS system in tandem with the existing density calibration procedures currently done with the existing NSTX MPTS system [28]. The only required extension to the existing technique for the DTS system would be to include both the Stokes and the anti-Stokes Raman spectra of N_2 in the analysis in order to calibrate the bandpass filter with CWL to the red (longer wavelengths) of the Nd:YAG laser line.

V. SUMMARY & FUTURE WORK

A divertor Thomson scattering diagnostic system for NSTX-U would be a greatly beneficial addition to NSTX-U with broad application to the divertor/boundary program. A conceptual design based on a tangential laser path through the torus and poloidally diagonal viewing optics has been proposed and described. Following approval by PPPL, a detailed optical design for the DTS system would be carried out in order to decide on collection optics dimensions and *f*/#, fiber bundle design, etc. The ex-vessel portion of the system is based significantly on the successful DTS design on the DIII-D tokamak which has been recently upgraded and demonstrated to achieve the design requirements proposed for NSTX-U, most notably accurate e measurement to 0.5 eV. With this performance, the DTS system is capable of measurements across divertor regimes to evaluate dominant physics processes into 'deep' detachment common with high density operation. Results from DTS would represent key input to the latest boundary modeling code suites for diagnosing and predicting divertor conditions. Furthermore, DTS measurements would be critical for interpretation of boundary phenomena related to lithium application, filtered impurity emission imaging, and the MAPP probe on NSTX-U.

VI. ACKNOWLEDGEMENTS

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